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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL NOTE

No. 1174

THE APPLICATION OF HIGH-TEMPERATURE STRAIN GAGES TO THE MEASUREMENT OF VIBRATORY STRESSES IN GAS-TURBINE BUCKETS

By R. H. Kemp, W. C. Morgan, and S. S. Manson

Aircraft Engine Research Laboratory
Cleveland, Ohio

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SUMMARY

The feasibility of measuring the vibration in the buckets of a gas turbine under service conditions of speed and temperature was determined by use of a high-temperature wire strain gage cemented to a modified turbosupercharger turbine bucket. A high-temperature wire strain gage and the auxiliary mechanical and electrical equipment developed for the investigation are described.

INTRODUCTION

Although vibrational fatigue affects the service life of the buckets of high-temperature gas turbines, little precise data are available on the magnitude of the vibration in the buckets during operation and on the factors that affect it. This deficiency exists because no satisfactory method of measuring the vibration under operating conditions has been available. A program including the measurement of the vibratory stresses in gas-turbine buckets during power operation of the turbine is therefore in progress at the NACA Cleveland laboratory.

A strain gage consisting of fine high-resistance wire wound on a suitable form and cemented to the surface of a test member offers considerable promise as an instrument for the measurement of vibratory stresses in turbine buckets. The change in the resistance of the wire serves as a measure of the strain at the point of application of the strain gage. Strain gages have been used extensively in reciprocating-engine and structural research for the determination of both static and dynamic strains. The strain gages developed for these comparatively moderate temperature applications are not, however, suitable for use on the buckets of a gas turbine in which temperatures above 1200° F are to be expected. It was therefore considered necessary to develop a high-temperature strain gage capable of withstanding operating temperatures as the first part of the program to investigate vibration phenomena in turbine buckets. Although development of the high-temperature strain gage is being continued, the strain gage now available is satisfactory for application to preliminary tests on turbosupercharger turbine buckets.

Preliminary results obtained from a modified turbosupercharger during operation under conditions of actual service are presented together with a description of the strain gage, the slip rings, and the electrical circuits.

INSTRUMENTATION

The instrumentation consisted of a high-temperature strain gage used as one arm of a Wheatstone bridge, vibration measuring and recording instruments, and slip rings for transmitting current from the strain gage to the instruments.

High-Temperature Strain Gage

The strain gages used in the tests consisted of 0.001-inch Nichrome V wire wound on a form of woven glass tape. In one test the strain gages were cemented to the turbine buckets with Sauereisen No. 78 cement. Sauereisen No. 1 cement was used in a similar test. The performance of strain gages is measured in terms of the ratio of the change of resistance to the change in length and this ratio is called the strain-gage sensitivity factor. A typical curve of the ratio of the strain-gage sensitivity factor at elevated temperatures k_T to the factor at room temperature k_0 as a function of temperature is shown in figure 1 for a strain gage cemented with Sauereisen No. 78 cement. A number of strain gages constructed without a winding form were also tested. These gages proved to have a superior strain-sensitivity characteristic at elevated temperatures but were difficult to make in gage lengths less than one-fourth inch. This type of strain gage was not used therefore in the turbosupercharger tests where physical considerations limited the gage length to one-eighth inch. A more detailed discussion of the strain-gage characteristics is given in appendix A.

Slip Rings

Transmission of the strain-gage current was accomplished by means of a slip-ring unit of the cylindrical type. All the rings were of the same diameter and contact was made through brushes mounted at an angle to the radii and in the plane of the slip ring to avoid the chattering effect sometimes encountered in applications in which the brushes are mounted in line with the radii. The materials used were monel metal for the slip rings and silver graphite for the brushes. Contact between the rotating rings and the stationary brushes was free of significant changes in electrical resistance at the high speeds of turbine operation.

Strain-Gage Circuit

Although the resistance characteristics of the slip-ring unit were very satisfactory, small changes in resistance were expected across the rings and brushes at high speeds of operation. Figure 2 shows the strain-gage circuit devised to conform to the results of an analysis (appendix B) of the significant factors in minimizing the effects of slip-ring resistance fluctuations.

Although only the high-temperature strain gage must necessarily be on the rotating member, the other three arms of the Wheatstone-bridge circuit should also be mounted on the rotating part to avoid slip-ring effects as much as possible. In these tests the three balancing arms of the bridge were strain gages mounted on the rotating part of the slip-ring assembly. A high resistance was placed in series with the direct-current power supply to the bridge to reduce still further the slip-ring effects. A direct-current supply of 240 volts was used with sufficient external resistance to drop the voltage across the strain-gage bridge to 18 volts.

Measuring Equipment

A cathode-ray oscilloscope in conjunction with a drum camera was used to observe and record the amplitude and wave form of the bucket vibration. The amplitude of the oscillograms was also determined by an rms vacuum-tube voltmeter. The sensitivity of the recording equipment was of the order of 1.30 millivolts per inch. The frequencies of the bucket vibrations were determined by comparison with a signal from a variable-frequency generator. A strain gage mounted on a steel cantilever flexed at 50 cycles per second provided a signal of known amplitude and frequency for calibration purposes.

TEST EQUIPMENT AND PROCEDURE

Turbine Modifications

The turbine wheel used for the investigation of vibration in turbine buckets was selected because it provided a means of checking the adequacy of the high-temperature strain gages and the accompanying instrumentation. In turbine wheels of the type used in the test unit the buckets are stiff and are supported at the outer ends by a segmented shroud ring. This construction is resistant to vibration. Excitation of the buckets by the intermittent gas loading is small because of the large number of nozzles and buckets in the unit. As a result, under normal conditions of operation no perceptible vibration of the buckets was expected. The stability of strain conditions during this normal operation would serve to check the instrumentation for the influence of any external effects not directly related to vibration, such as slip-ring resistance changes, interference from electronic equipment used in amplifying and recording, and interference from other electric devices installed near the test equipment. By means of modifications to the buckets and to the nozzle ring, however, severe conditions of vibration could be induced and the performance of the strain gages and auxiliary instruments under this type of operation could be observed.

Figure 3(a) shows one of the test buckets modified by reducing the cross-sectional area near the root. This change lowered the first-mode natural frequency of the bucket to approximately 1000 cycles per second, thus bringing it within the excitation range of the test conditions. Strain gages were mounted at the weakened sections on the concave sides of the buckets. Figure 3(b) shows the installation in which the buckets immediately adjacent to the test bucket were removed to eliminate the support of the shrouding. The bases of these adjacent buckets were inserted in the wheel to prevent distortion in the retaining slots of the test buckets. The lead wires from the strain gage were insulated from the wheel and cemented to the wheel with the same type of cement used in mounting the strain gage. The wires were then led into a hub on the wheel and through a hollow shaft to the slip rings. The modification made to the nozzle box is shown in figure 3(c). Four plates, each covering 45° of the nozzle-box opening, were welded to the box at equally spaced intervals. Because of the partial admission of the gases caused by this modification, a large fluctuation of gas-pressure loading on the turbine buckets was produced during operation.

Test Installation

A photograph of the test installation is presented in figure 4. The principal components were a jet burner to supply hot gases under pressure, an aircraft-engine turbosupercharger, and equipment required to load the turbine. The jet burner supplied the turbine with gases at a nozzle-box inlet temperature of 1500° F. After passing through the turbine, the gases were discharged into an exhaust system maintained at low pressure.

Tests

Tests were made on a standard turbine and on one that had been modified as previously described. In the tests made on the modified turbine wheel, gages cemented with both Sauereisen No. 1 and No. 78 were used. The test procedures were similar; the turbines were operated at full load over speeds ranging from 5000 to 20,000 rpm and all vibration phenomena were observed and recorded.

RESULTS AND DISCUSSION

The test on the standard turbine wheel was intended as a check to verify the premise that a strain-gage signal would be obtained only as the result of actual vibratory stress in the bucket and not of slip-ring effects or of extraneous interference. Because no significant signal was obtained in the range of speeds from 5000 to 20,000 rpm, it was concluded that the instrumentation was satisfactory for tests of vibratory stress.

Modifications to the test turbine wheels were especially conducive to the introduction of vibratory-stress conditions in the buckets. An idealized pressure diagram across the test bucket would be represented by a square wave. During the period when the bucket is passing the uncovered nozzles, the pressure is sensibly uniform and relatively high; whereas, during the period when the bucket is passing the covered nozzles, the pressure reduces to nearly zero. If the frequency of pressure fluctuation or any harmonic thereof coincides with the natural frequency of the bucket, the bucket would be excited into resonant vibration. A Fourier analysis of the pressure diagram indicates that at any resonance the natural frequency of the bucket would be an integral multiple of the turbine rotational frequency.

The results presented were obtained with strain gages cemented with Sauereisen No. 78 cement. The test made with Sauereisen No. 1 cement as the gage-bonding material yielded quantitatively similar results. Figure 5 shows the spectrum of frequencies for which resonances were observed on the modified bucket. The points A to E indicate the turbine speeds at which the resonances occurred and the natural frequency of the bucket at each of the resonant speeds. The curve through the points A to E therefore represents the variation in natural frequency of the bucket with turbine speed. The fact that centrifugal force raises the natural frequency of the bucket is evident from the upward slope of the line. The dashed lines in figure 5 show the various harmonic orders of the turbine speed. For example, the ordinate of each point on the line of fourth harmonic order represents a frequency four times the turbine rotational frequency. It would be expected, therefore, that each of the observed resonances A to E should be on one of the integral harmonic-order lines, as is seen to be the case.

The measured total range of stress at each resonance is tabulated in figure 5. In order to calculate the stresses it was necessary to know the strain-gage sensitivity factor at the temperature of the bucket and this factor was determined from figure 1 after a determination of the sensitivity factor of the strain gage at room temperature was made. The room-temperature sensitivity factor was measured by observing the output of the strain gage when a known weight was suspended from the end of the bucket and comparing the value with the calculated stress at the strain-gage position. The room-temperature strain-gage sensitivity factor was thus found to be 1.75. The stresses in the vibrating bucket at elevated temperatures were calculated by assuming a bucket temperature of 1200° F inasmuch as a nozzle-box inlet temperature of 1500° F was maintained throughout the tests. The values for the strain-gage sensitivity factor and the modulus of elasticity of the bucket used to calculate the stresses were therefore chosen for 1200° F. If a bucket temperature of 1100° F had actually existed, the errors in the computed stresses would be of the order of 2 percent, whereas had a temperature of 1300° F actually existed the error would be of the order of 10 percent.

The exact peak stress at each resonance was immeasurable because the resonance was very critical with respect to speed and the speed controls available were insufficiently sensitive to obtain exact resonance. Furthermore, the vibration was so severe at the fourth-order resonance as to render it inadvisable to permit the amplitude to build up to a maximum. The bucket ruptured during the last run, just after the near-resonance stress (40,200 lb/sq in.) shown in figure 5 was observed. It may be noted, however, that the strain gage was still in good condition after the bucket ruptured; the rupture was located immediately above the gage position. In all cases the vibratory strain signal was clear and free of foreign interference such as slip-ring effects.

SUMMARY OF RESULTS

The satisfactory detection and determination of vibratory stresses on a test setup at actual specimen temperatures up to 1500° F has been accomplished by means of a high-temperature wire strain gage. The strain gage was also applied satisfactorily on gas-turbine buckets operating at speeds encountered in actual service and at a nozzle-box inlet temperature of 1500° F. The strain signals from the strain gages cemented to the buckets were transmitted free of any interference to the measuring instruments through slip rings.

Aircraft Engine Research Laboratory,
National Advisory Committee for Aeronautics,
Cleveland, Ohio, February 14, 1947.

APPENDIX A

CONSTRUCTION AND CALIBRATION OF HIGH-TEMPERATURE STRAIN GAGE

Construction

Materials. - The objective in the development of the high-temperature strain gage was to determine a suitable wire, wire form, and cement that would permit the measurement of vibratory stresses in gas-turbine buckets subjected to gas temperatures in the neighborhood of 1500° F. A large number of combinations of wires and cements was tested; of these, Nichrome V wire wound on a woven glass-tape form and cemented with either Sauereisen No. 1 or Sauereisen No. 78 cement proved to be the most satisfactory combinations to date.

Method of construction. - The strain-sensitive filament is prepared by resistance-welding lead wires to the ends of a 120-ohm length of 0.001-inch-diameter Nichrome V wire. Depending upon the specific requirements, either 0.010-inch-diameter Nichrome V wire or 0.010-inch-diameter nickel wire is used for the lead wires. The Nichrome V lead wire is preferable because of its superior high-temperature characteristics but when long leads are required the lower resistance nickel wire is used. When gage lengths of one-fourth inch or greater can be used, the loops of the strain-sensitive wire are held in place by strands of hair or wire and the gage is cemented to the test specimen, a multiple-loop winding thus being formed. Because the gage length depends upon the number of loops, fabrication of a strain gage with a gage length smaller than one-fourth inch becomes difficult. Gages smaller than one-fourth inch in length are therefore fabricated by winding the strain-sensitive wire upon an insulating form prepared from glass-fiber tape impregnated with the Sauereisen cement and baked at 225° F for 1/2 hour. A strip of the prepared tape 0.125 inch wide and approximately 1.5 inches long is sanded smooth and clamped with slight longitudinal tension between the jaws of a device that permits the strip to be rotated. The lead wires are then fastened to the strip as shown in figure 6. The end of the lead to which the resistance wire is fastened is held in the correct position while the lead wire is turned twice around the insulating strip. The resistance wire is pulled into a V-shape by a hook on the end of a piece of wire, as shown in figure 6. The insulating strip is then rotated and the wire automatically spaces itself as it is wound. Upon completion of the winding operation, the loop in the resistance wire is fixed in place by a wire threaded through the loop and pulled into a notch at the edge of the tape. The upper face of the strain gage is covered with a thin coat of Sauereisen cement and is baked at 225° F for 1 hour. After removal of the excess portions of the insulating form, the strain gage is ready for the mounting procedure. Strain gages of 1/8-inch gage length were used for the turbine-bucket tests but other sizes can be constructed by the same method.

Mounting. - The metal surface to which the strain gage is to be attached is prepared by sanding with a fine grit paper, cleaning with ethyl alcohol, and also using the Sauereisen cement as a cleaner. A thin, smooth coat of cement is then brushed on to the metal surface and baked at 250° F for 16 hours. When mounting the form-wound type of strain gage a second thin coat is applied, the strain gage is placed in position, and a small amount of cement is brushed over the strain gage. The strain gage is then tightly clamped using a clamping pad of 1/4-inch felt covered with a sheet of neoprene. After air drying has proceeded for approximately 1 hour, the clamp is removed and the mount is baked at 250° F for 16 hours. Fixing the lead wires in position by methods such as cementing or wiring completes the strain-gage installation. The foregoing cycles of temperatures and baking times have been found satisfactory for application of the strain gage either with the Sauereisen No. 1 or No. 78 cement; however, the cycles are not critical and other combinations are possible. For application with the No. 1 cement it is recommended that the mounted strain gage be baked at 1400° F for 15 minutes for reasons that are subsequently discussed.

Calibration

A dynamic calibration was made to determine the effect of temperature upon the strain sensitivity of the high-temperature strain gage. The test strain gages were mounted on a cantilever bar of Inconel that was flexed to a constant tip amplitude at a frequency of 20 cycles per second. The section of the bar upon which the strain gages were mounted was enclosed by a furnace with suitable temperature control to permit variation of the temperature of the bar in the region of the strain gages from room temperature to 1500° F. A small steel beam with an attached bakelite-impregnated strain gage transferred the flexing force from the cam to the Inconel bar. The bakelite-impregnated strain gage, remaining at a relatively low temperature and at constant strain sensitivity, provided a measure of the flexing force applied to the end of the test bar and therefore of the stress in the outer fiber of the bar at the location of the test strain gage. Figure 7 illustrates the test setup and the electrical strain-gage circuit.

When the circuit is completed by the high-temperature strain gage, the voltage appearing across the voltmeter as the test bar is flexed by the cam is proportional to the product of the strain-gage sensitivity factor and of the strain. The strain is equal to stress divided by the elastic modulus, whereas the stress is proportional to the voltmeter reading when the circuit is completed by the bakelite-impregnated strain gage. The following equation can therefore be written

$$\frac{V_{aT}}{V_{a0}} = \frac{k_T}{k_0}\,\frac{V_{bT}}{V_{b0}}\,\frac{E_0}{E_T} \tag{1}$$

or

$$\frac{k_T}{k_0} = \frac{V_{aT}}{V_{a0}}\,\frac{V_{b0}}{V_{bT}}\,\frac{E_T}{E_0} \tag{2}$$

where

k_T sensitivity factor of high-temperature strain gage at temperature T

k_0 sensitivity factor of high-temperature strain gage at room temperature

V_{aT} voltmeter reading when circuit is completed by high-temperature strain gage at temperature T

V_{a0} voltmeter reading when circuit is completed by high-temperature strain gage at room temperature

V_{bT} voltmeter reading when circuit is completed by force-measuring strain gage while high-temperature strain gage is at temperature T

V_{b0} voltmeter reading when circuit is completed by force-measuring strain gage while high-temperature strain gage is at room temperature

$\frac{E_T}{E_0}$ ratio of elastic modulus at elevated temperature to elastic modulus at room temperature (The curve for Inconel, as obtained from reference 1, is shown in fig. 8.)

Equations (1) and (2) are strictly correct only if the direct current resistance of the high-temperature strain gage remains constant as the temperature is varied. Actually the resistance increases as the temperature is increased and a slight error occurs if equation (2) is used to determine k_T/k_O. The error is in the order of less than 1 percent for strain-gage resistance variations as high as 25 percent; therefore, equation (2) may be considered sufficiently accurate for practical purposes. In this analysis the dropping resistor R_d has been considered equal to the strain gage R_{bO}.

Properties

The life of the strain gages at elevated temperatures was found to be dependent upon the manner in which the strain gages were connected into the electrical circuit. As an example, several filament-type strain gages were operated at 1500° F for 15 hours with satisfactory quantitative results, but when a minor change was made in the electrical circuit, the strain gages failed within a few minutes. Microscopic examination of the strain gages after failure showed severe corrosion of the strain-sensitive wire. Figure 9 shows variations of the common potentiometer circuit that were tested to determine the critical factor in the corrosion process. When the circuits of figures 9(a) and 9(b) were used, no failure resulted and there was no detectable corrosion; when the circuits of figure 9(c) were tested, the strain gages failed at approximately 1200° F. Inspection of the circuits shows that the failures occurred when the average potential of the strain-sensitive filament was negative with respect to the test specimen (ground) but did not occur when the average potential was positive with respect to the test specimen. Operation without circuit grounding (fig. 9(b)) was successful regardless of the battery polarity.

The corrosion may be explained by comparing it to an electrolytic effect in which the strain-sensitive filament and the test specimen act as the electrodes whereas the Sauereisen cement acts as the electrolyte at the elevated temperatures. The equivalent circuit is illustrated in figure 10, which shows both the correct method of connecting the circuit (fig. 10(a)) and the incorrect method (fig. 10(b)). Wheatstone-bridge circuits, common in strain-gage circuits involving the use of slip rings, must likewise be so arranged that the average potential of the strain gage is positive with respect to the test surface.

The variation of the resistance with temperature of the high-temperature strain gages fabricated with Nichrome V wire is shown in figure 11. It is noted that during the first half of cycle 1 an increase in the resistance of approximately 17 percent is obtained. Upon completion of cycle 1 (return to room temperature) the resistance was found to return to a value approximately 12 percent higher than the original. In subsequent heating and cooling cycles the trend of the second half of cycle 1 is retained as shown in figure 11 by cycle 2.

The strain sensitivities of the strain gages at elevated temperatures were plotted as the ratio of the sensitivity factor at the elevated temperature to the sensitivity factor at room temperature. This method provides a means of comparing the strain sensitivities at elevated temperatures of various strain gages that have different room-temperature strain sensitivities. The strain-sensitivity factors at room temperature of the form-wound strain gages tested were 1.75 ±10 percent. If the gage factor in a specific application cannot be measured, a value of 1.75 is recommended for a form-wound gage. The effect of temperature upon the strain-sensitivity factor of a typical Nichrome V filament-type strain gage (without winding form) cemented with Sauereisen No. 1 is shown in figure 12. A relatively constant sensitivity factor was obtained up to 1500° F and subsequent temperature cycling had no effect upon the uniformity of the sensitivity factor. At room temperature, the average sensitivity factor was 2.05 with a variation from gage to gage of approximately ±5 percent. Gages cemented with Sauereisen No. 78 cement gave quantitatively similar results.

The variation of the ratio of strain-sensitivity factors k_T/k_O with temperature for strain gages cemented with Sauereisen No. 78 cement is shown in figure 13. Two complete heating and cooling cycles are shown with a temperature range from room temperature to 1500° F. The sensitivity factor is sensibly stable and reproducible throughout the heating and cooling cycles. The wave form of the strain-gage signal during testing was equally as good at 1500° F as it was at room temperature.

The variation of k_T/k_O with temperature for form-wound strain gages cemented with Sauereisen No. 1 is shown in figure 14. A sharp rise occurs during the first increase in temperature at approximately 1300° F but when cooled this rise disappears. For this reason, it is recommended that the specimens upon which strain gages are cemented with Sauereisen No. 1 be preheated to approximately 1400° F for a short time before actual testing. The variation of the strain sensitivities during subsequent heating and cooling cycles will be substantially the same.

The reproducibility of k_T/k_O from strain gage to strain gage of the form-wound type is such that accurate quantitative data can be obtained up to 1200° F. From 1200° to 1500° F variations occur and vibratory stress data obtained with such gages should be treated qualitatively. Inherent physical characteristics of the woven-glass form on which the resistance wire is wound causes the decrease of sensitivity factor with increase of temperature above 1200° F. The measurement of the frequency of the vibration is accurate up to 1500° F. It is recommended that whenever possible, a strain gage without winding form be used because accurate quantitative data can be obtained with this type up to 1500° F.

The choice between Sauereisen No. 1 and Sauereisen No. 78 cement depends upon the particular application. Sauereisen No. 78 cement has better cement-to-metal adhesive qualities than No. 1, but the No. 1 has better cement-to-cement adhesion than the No. 78. The No. 78 is also more hygroscopic and, if there is any moisture near the test installation, its use should be avoided. The addition of Sauereisen No. 15 thinner to the No. 78 cement has a detrimental effect upon the strain-gage sensitivity factor at elevated temperatures. The No. 78 cement is therefore more difficult to apply and good reproducible strain-gage mounts are likewise more difficult to obtain. In most applications the use of No. 1 cement is recommended. In the tests where No. 78 cement was used, it was found desirable to direct the heat of an infrared lamp on the strain-gage installation during the nonrunning periods. Satisfactory adhesion of the Sauereisen No. 1 and No. 78 cements has been obtained on such high-temperature alloys as 17W, Timken, Vitallium, and Inconel.

APPENDIX B

SLIP-RING EFFECTS

Because of the need for conducting currents and voltages between the stationary equipment and the rotating strain gage, slip rings are necessarily a part of strain-gage circuits. The interference effects of slip rings on strain-gage signals at high speeds of rotation can be minimized by reducing the resistance fluctuations between the slip rings and brushes themselves and by arranging the electrical circuit to be as insensitive as possible to the resistance fluctuations that do occur. Experience has indicated that the combination of monel-metal slip rings and silver-graphite brushes would serve satisfactorily for the present problem.

One method now in common use for minimizing the effect of slip-ring resistance variation is the mounting of the entire strain-measuring Wheatstone bridge on the rotating member. In the present application, three similar strain gages were cemented to the end face of the cylinder formed by the slip rings and slip-ring insulators. Because there was no vibratory strain in this cylinder the strain gages could be used as the fixed resistors R_2, R_3, and R_4. (See fig. 2(b).)

The use of a ballast resistor R (fig. 2(b)) in series with the power supply also serves to reduce the effect of variation in resistance between slip rings and brushes. The resistance variations then become a small percentage of the total resistance in the power-supply circuit and the voltage E_{AC} across the bridge remains more nearly constant than it would if the ballast resistor R were omitted. A quantitative analysis to show the effect of the ballast resistor is as follows:

The output voltage E_{BD} of the bridge can be shown to be

$$E_{BD} = \frac{E_v(R_4R_2 - R_1R_3)}{(R_1 + R_2)(R_3 + R_4) + R(R_1 + R_2 + R_3 + R_4)} \tag{3}$$

The output voltage of the bridge E_{BD} is therefore dependent upon the two variables R_1 and R. The fluctuation in E_{BD} caused by the variable R_1 is the desired strain-gage signal, whereas the fluctuation in E_{BD} caused by the variable R is the undesired slip-ring effect. If dR is the change in R, the fluctuation dE_{BD} caused by dR can be written

$$dE_{BD} = \frac{\partial E_{BD}}{\partial R} dR = -E_{BD} \frac{dR}{R'} \tag{4}$$

where

$$R' = R + \frac{(R_1 + R_2)(R_3 + R_4)}{R_1 + R_2 + R_3 + R_4} \tag{5}$$

From equations (4) and (5), it is evident that dE_{BD} as caused by dR can be reduced by decreasing E_{BD} and dR and by increasing R'. If the bridge is in near balance under the operating conditions, then E_{BD} will be close to zero. The bridge can be operated very close to the balance point by selecting R_2 equal to the resistance of the strain gage R_1 at the operating temperature and selecting $R_3 = R_4$. Because R_2 is usually mounted in a cool region, whereas R_1 operates at a high temperature that causes its resistance to increase, R_2 should theoretically have a higher resistance at room temperature than R_1. For practical purposes it is sufficient to select $R_1 = R_2 = R_3 = R_4$ at room temperature. The variation in slip-ring-brush resistance dR depends entirely upon the design of the brush and slip-ring combination. For the purpose of these tests the monel-metal slip ring and the silver-graphite brushes (two parallel brushes per ring) were found to be satisfactory.

The greater the resistance of the ballast resistor R, the less will be the effect of the resistance fluctuation dR. The limitation to the indefinite increase of R lies in the fact that, for sensitivity of the bridge to strain in the strain gage, the voltage across the bridge E_{AC} must be maintained constant. An increase in R must therefore be accompanied by a corresponding increase in the power-supply voltage E_v. In the present tests 240 volts were available. Because only 18 volts were necessary for adequate sensitivity of the bridge, 222 volts were available for the ballast resistor. An effective ballast resistance of 1500 ohms was used to obtain this voltage distribution. This resistance reduced the fluctuations in output voltage that resulted from slip-ring resistance fluctuations to about 15 percent of the value for the case of zero ballast resistance.

REFERENCE

1. Schabtach, Carl, and Fehr, R. O.: Measurement of the Damping of Engineering Materials During Flexural Vibration at Elevated Temperatures. Jour. Appl. Mech., vol. 11, no. 2, June 1944, pp. A86-A92.

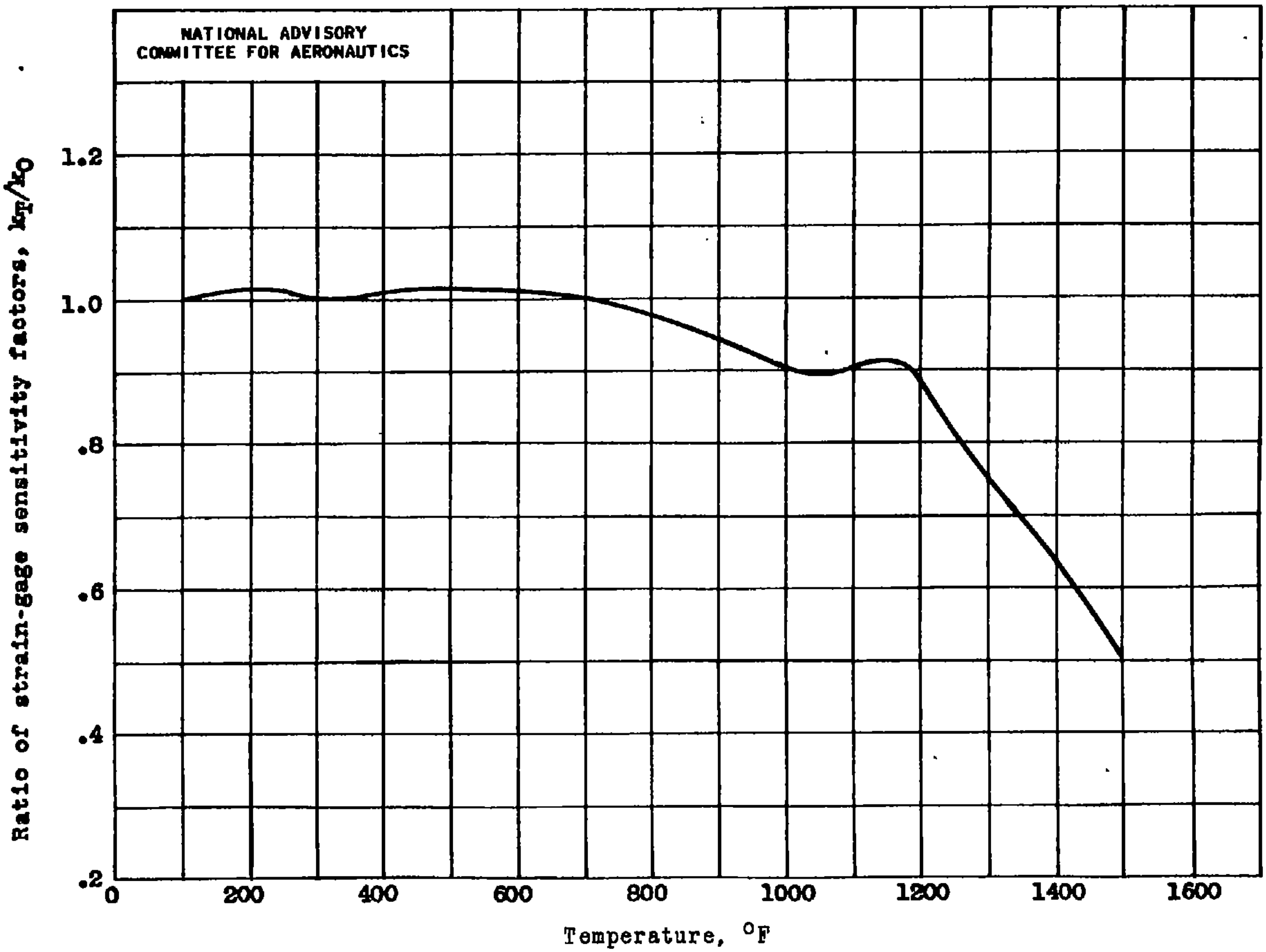
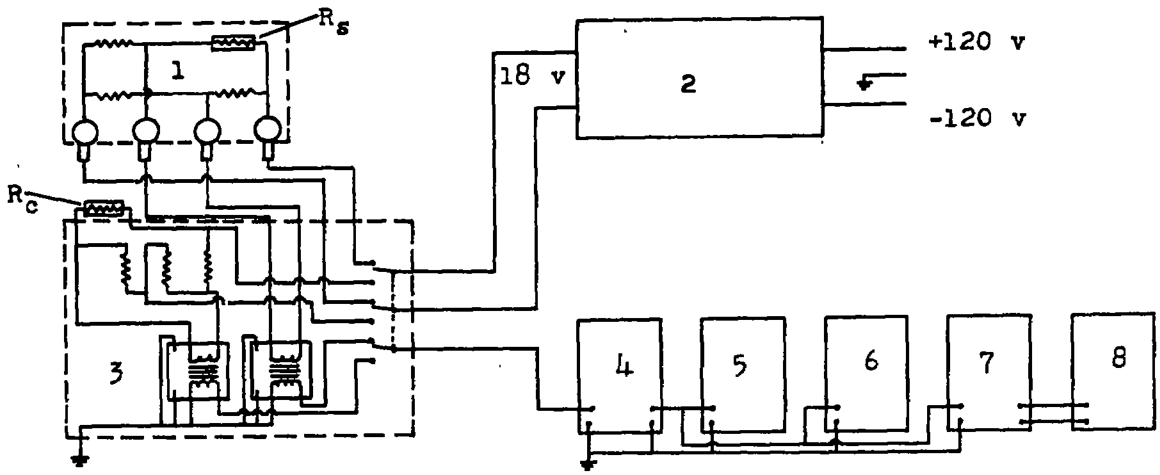
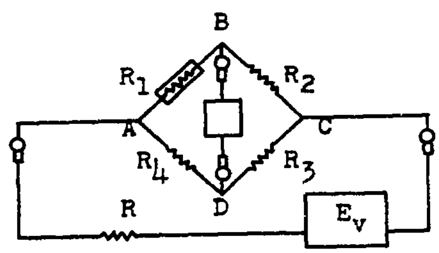


Figure 1. - Average variation with temperature of ratio of strain-gage sensitivity factor at elevated temperatures to strain-gage factor at room temperature for form-wound strain gages cemented with Sauereisen No. 78 cement.



1 Rotating system
2 Power supply
3 Control circuit
4 Amplifier
5 Oscillograph
6 Vacuum-tube voltmeter
7 Oscilloscope
8 Signal generator
R_s High-temperature strain gage
R_c Calibrator strain gage

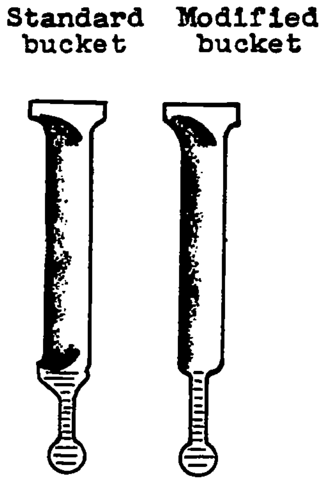
(a) Instrumentation.



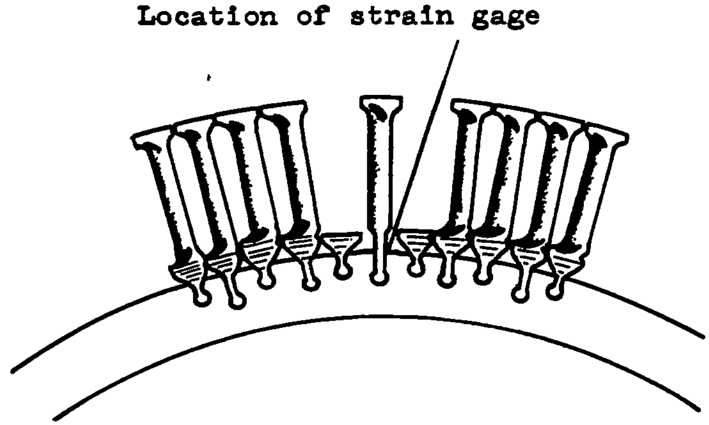
R Ballast resistor
R_1 Strain gage
R_2, R_3, R_4 Fixed resistors
E_v Power supply

(b) Equivalent circuit for analytical purposes.

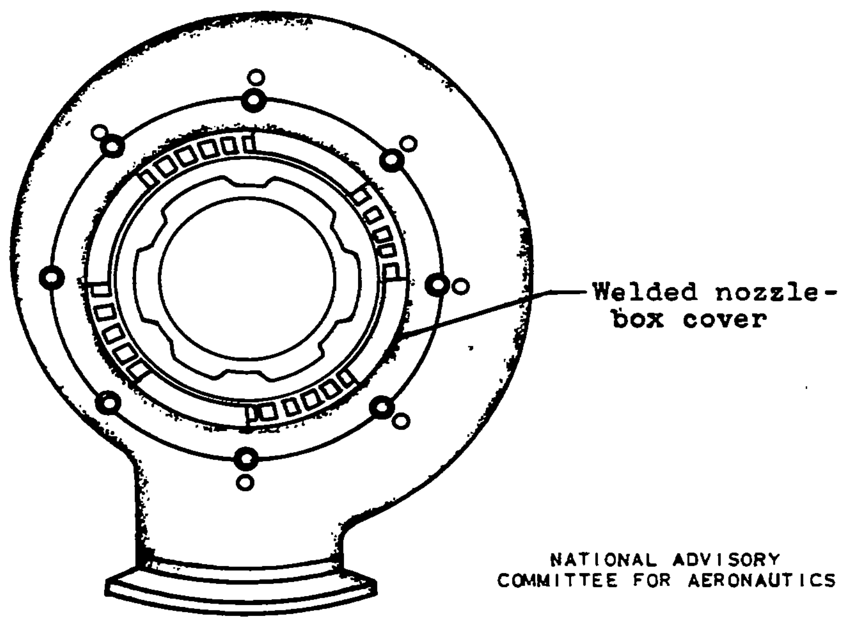
Figure 2.- Instrumentation and circuits used in the investigation of vibratory stresses in turbine buckets.



(a) Modification of test bucket.



(b) Section of turbine wheel showing modified, stub, and standard buckets.



(c) Modified turbine nozzle box.

Figure 3. - Modifications made to turbine bucket, wheel, and nozzle box.

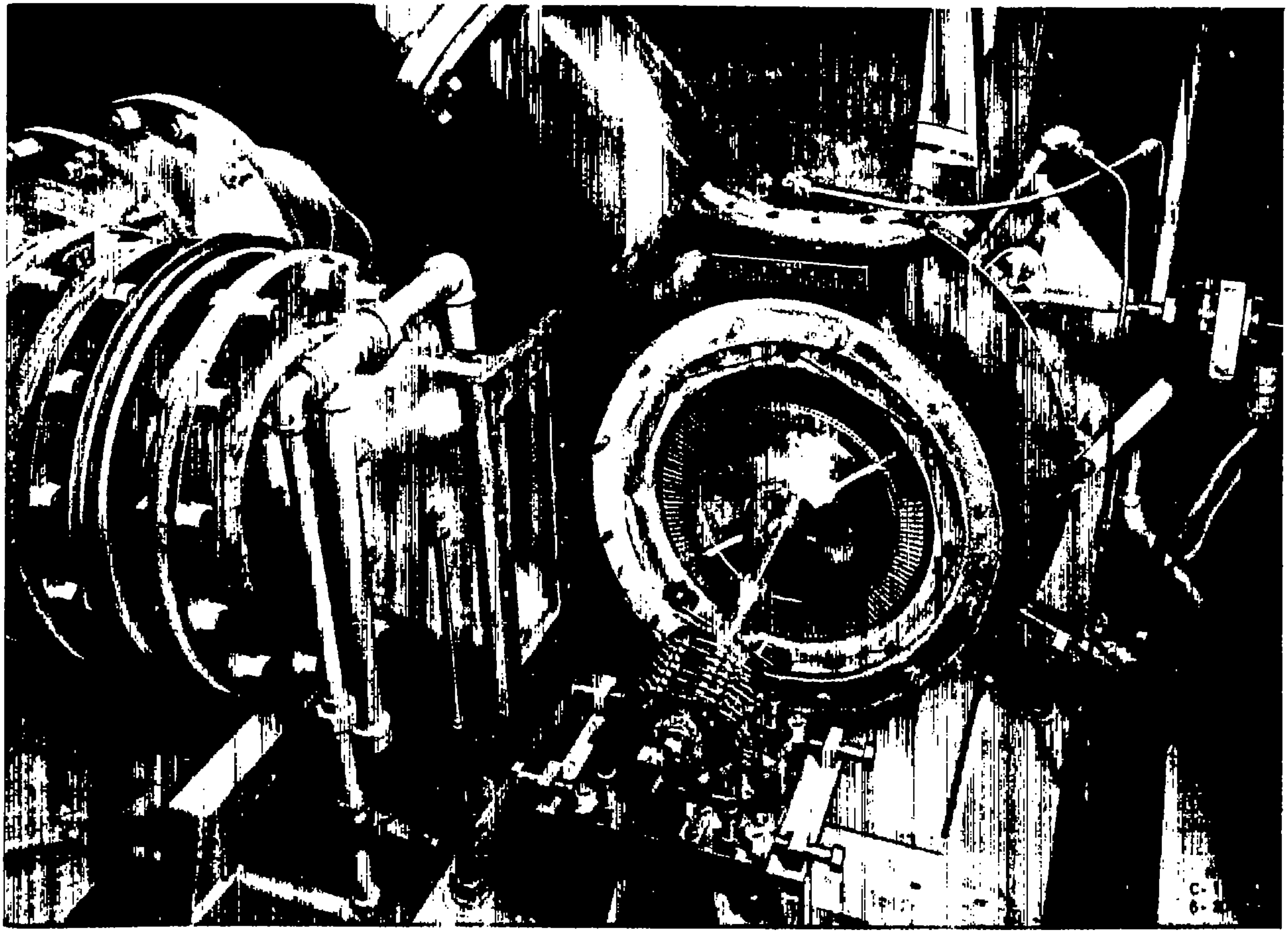


Figure 4. - Test installation showing modified turbine wheel and slip-ring assembly.

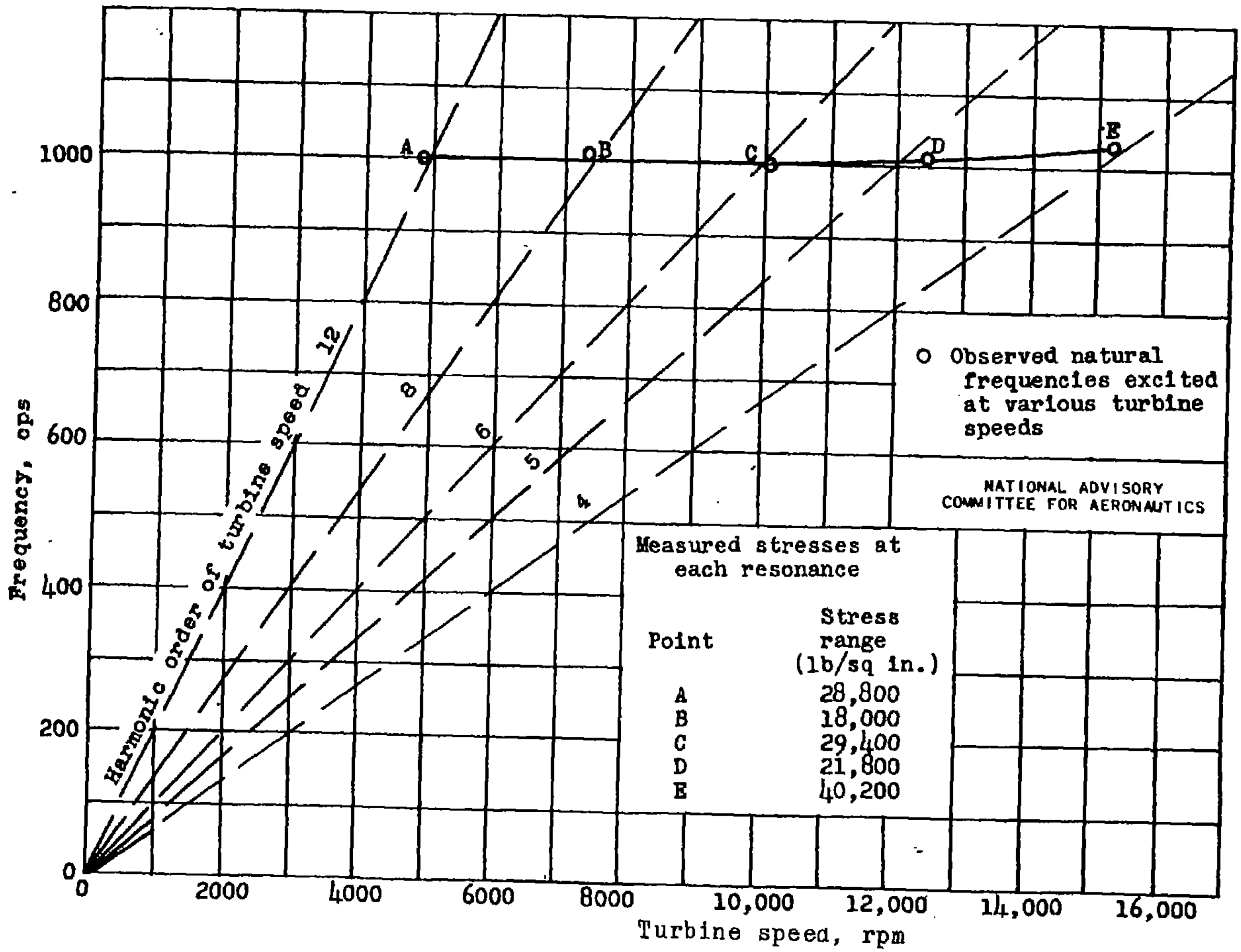
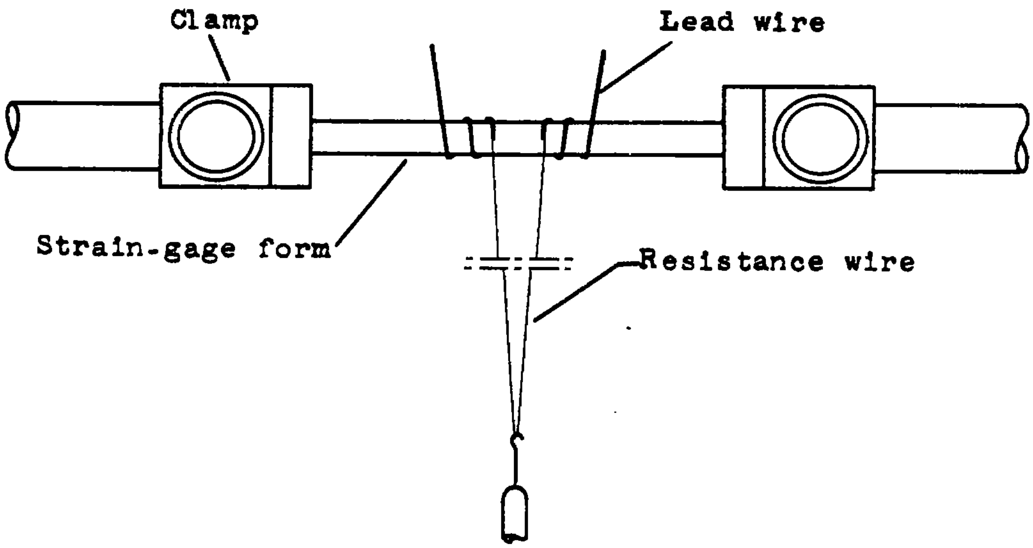


Figure 5. - Resonance spectrum for modified turbosupercharger turbine bucket.



(a) Strain-gage form clamped with wires prepared for winding.

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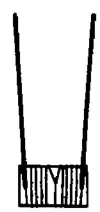

(b) Completed strain gage.

Figure 6.- Construction of high-temperature strain gage.

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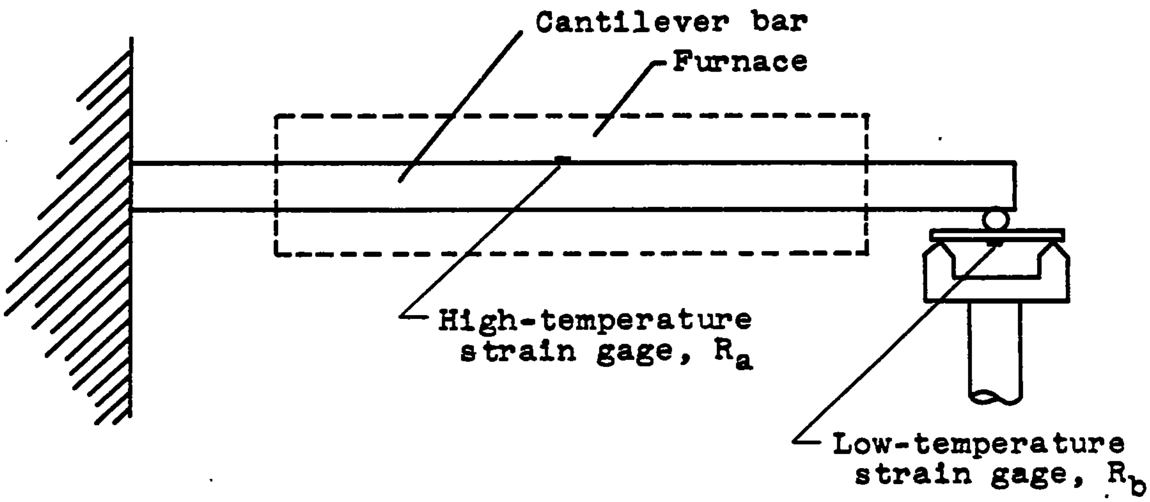
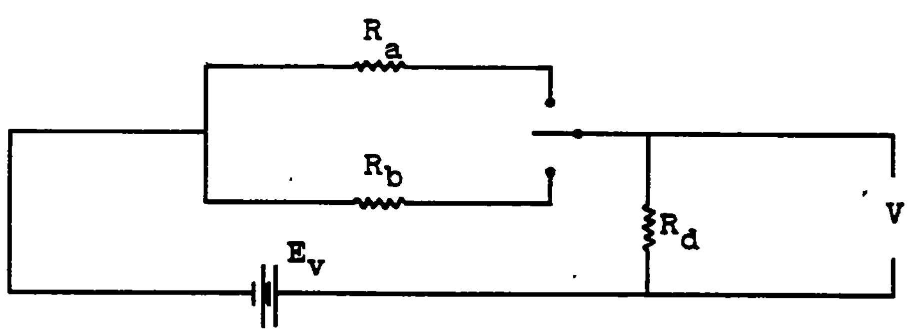


(a) Essential parts of calibration setup.



(b) Equivalent circuit.

Figure 7.- Calibration setup and electrical circuit used in determining the sensitivity of the high-temperature strain gage.

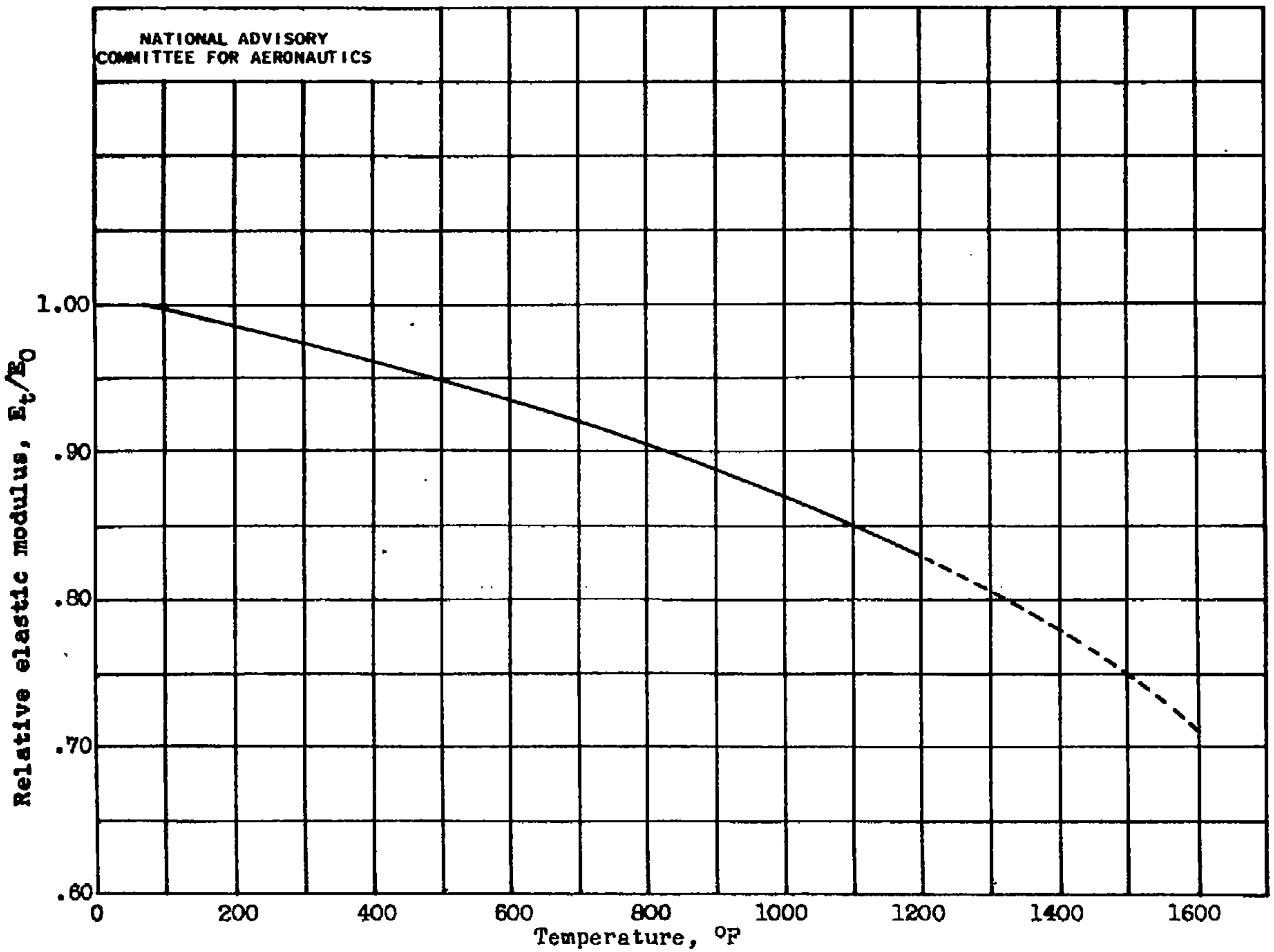
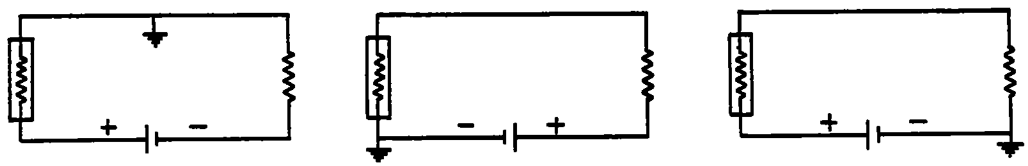
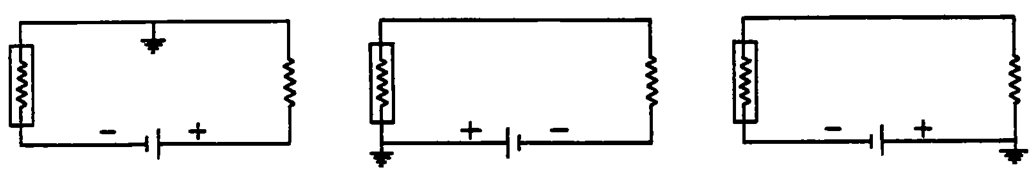


Figure 8.- Variation of elastic modulus of Inconel with temperature. (Taken from reference 1.)



(a) Battery polarity in grounded circuits that operated satisfactorily at 1500° F.

(b) Battery polarity in ungrounded circuits that operated satisfactorily at 1500° F.



(c) Battery polarity in grounded circuits that failed at approximately 1200° F.

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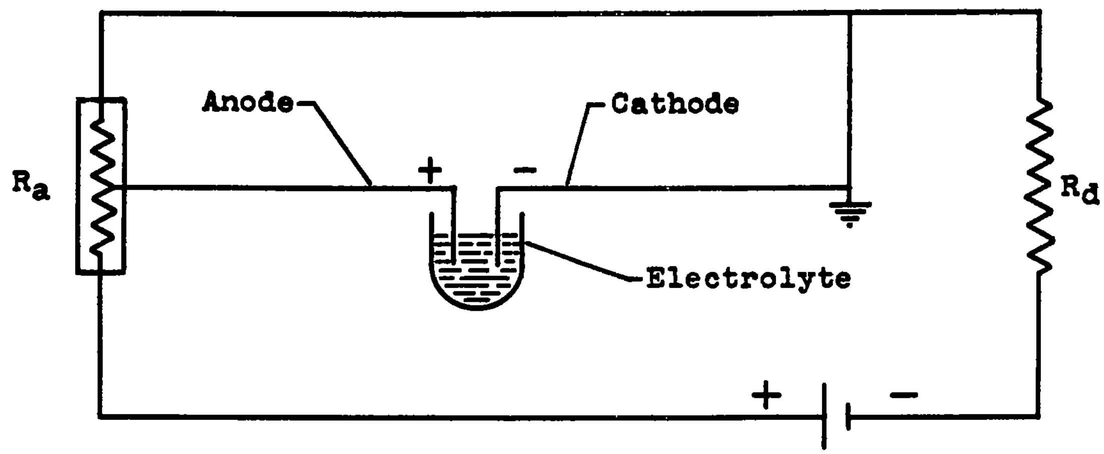
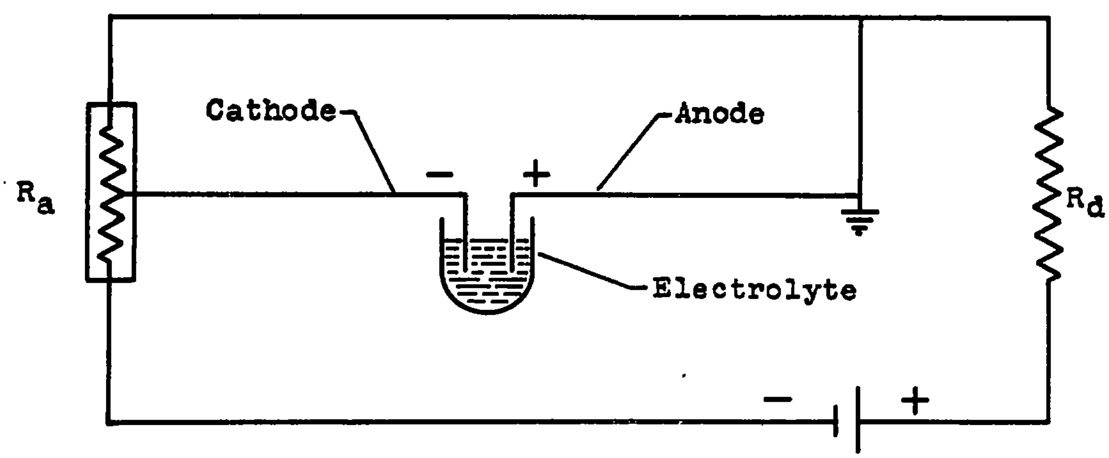
Figure 9. - Schematic diagrams of eight strain-gage potentiometer circuits tested to determine the effect of battery polarity.



(a) Average strain-gage potential above ground.



(b) Average strain-gage potential below ground.

Figure 10. - Polarity effect of high-temperature strain gage.

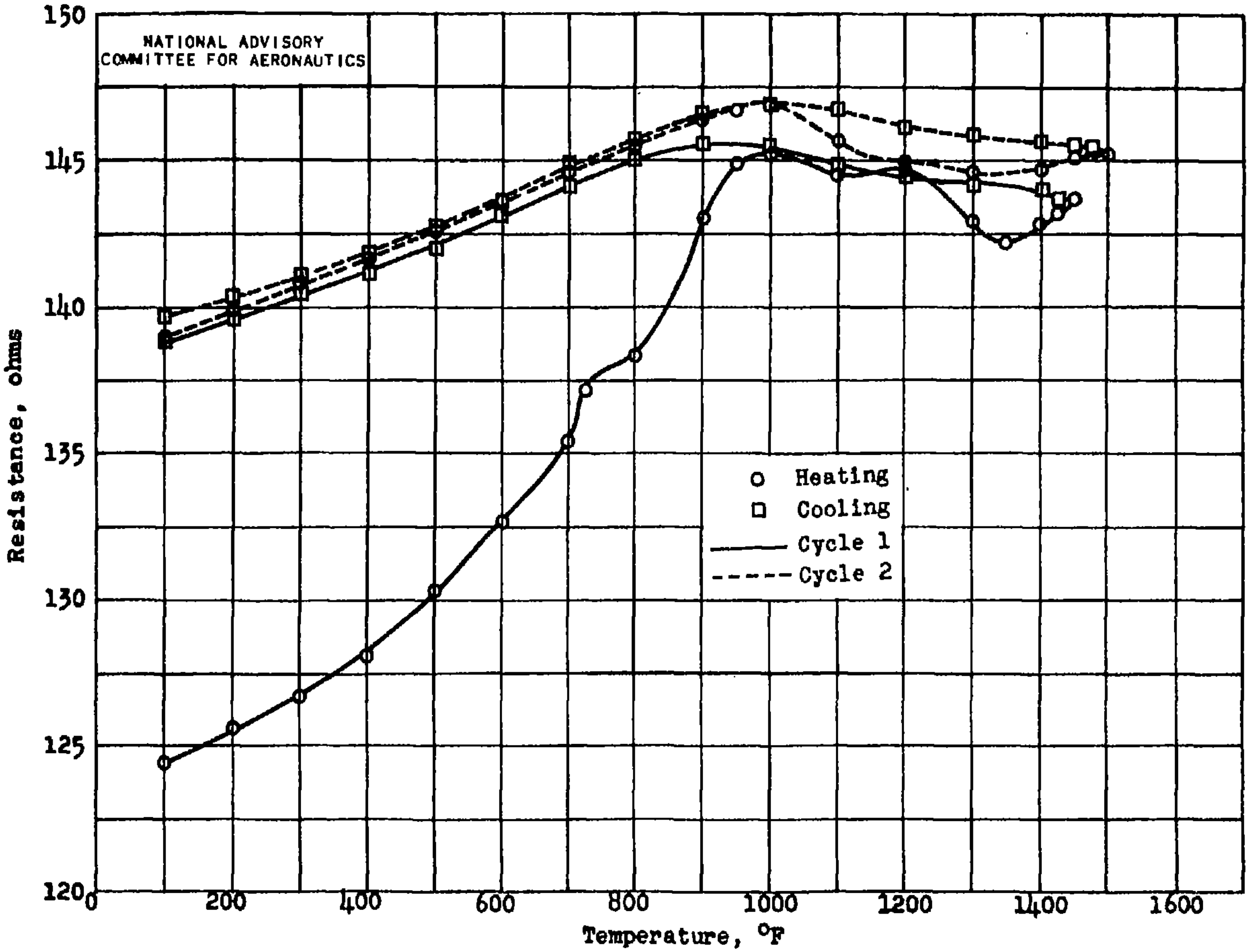


Figure 11.- Variation of resistance of a Nichrome V wire strain gage with temperature.

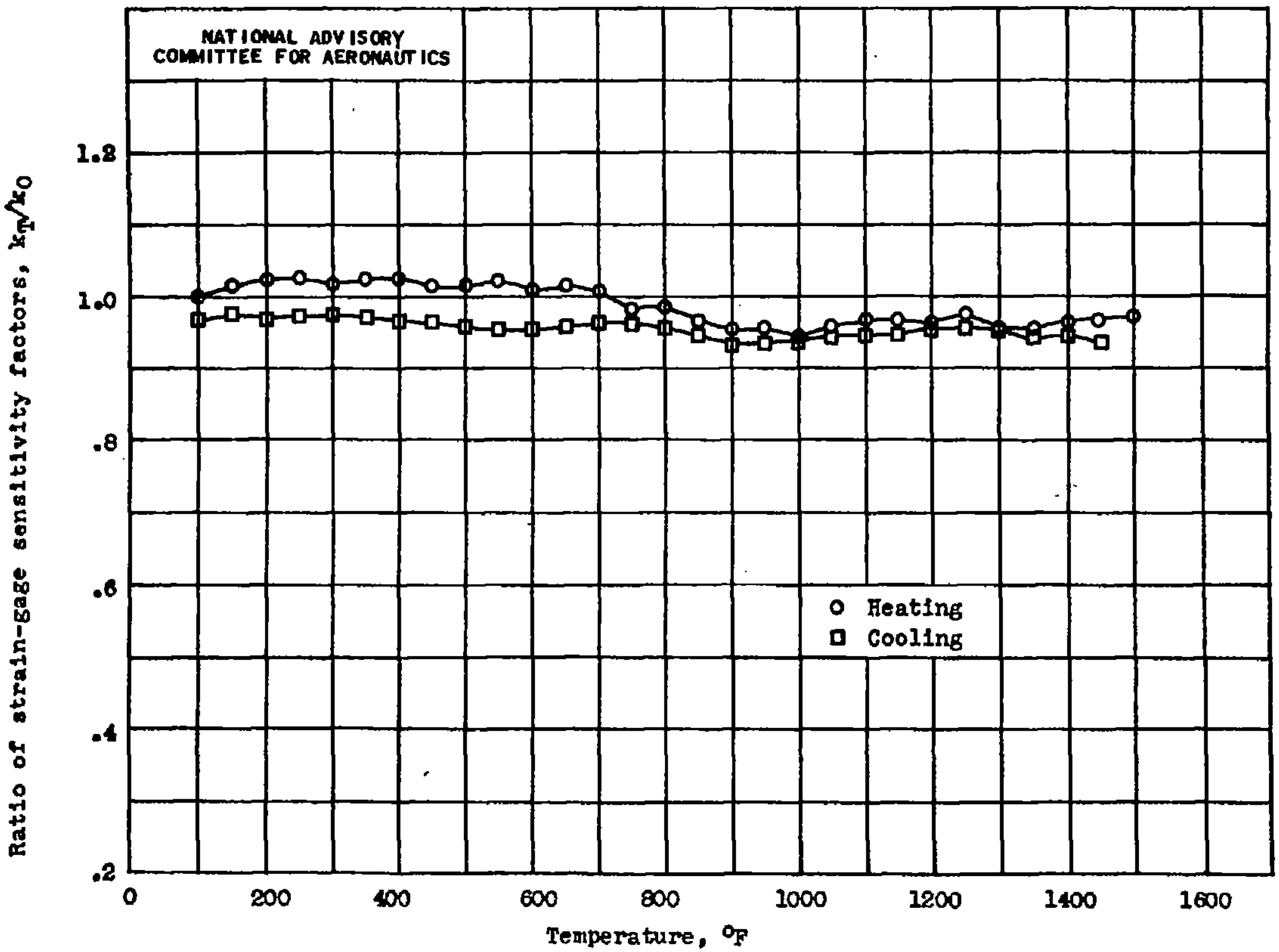


Figure 12. - Variation of ratio of strain-gage sensitivity factor at elevated temperatures to factor at room temperature with temperature for strain gages without winding forms cemented with Sauereisen No. 1 cement.

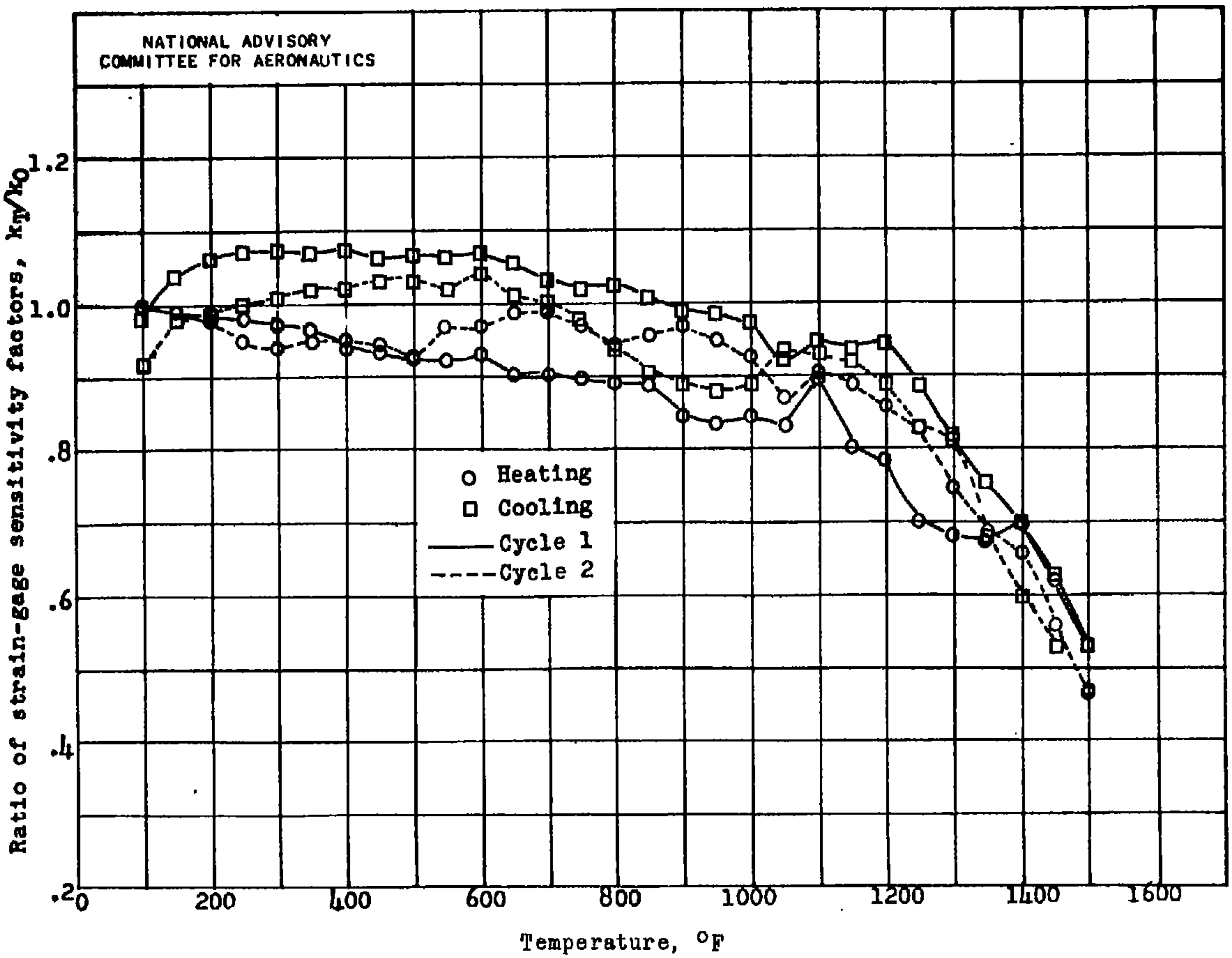


Figure 13. - Variation of ratio of strain-gage sensitivity factor at elevated temperatures to factor at room temperature with temperature for form-wound strain gages cemented with Sauereisen No. 78 cement.

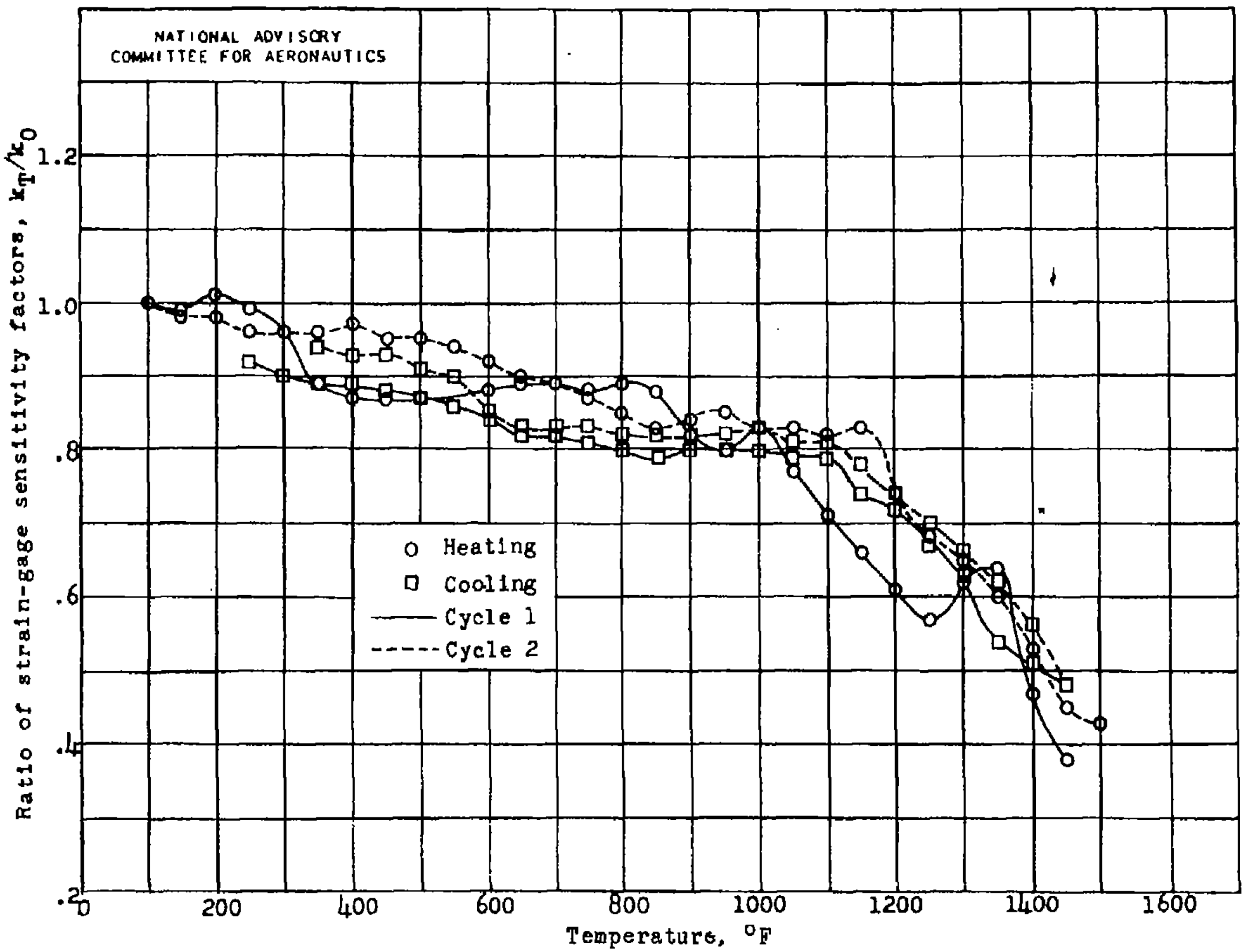


Figure 14. - Variation of ratio of strain-gage sensitivity factor at elevated temperature to factor at room temperature with temperature for form-wound strain gages cemented with Sauereisen No. 1 cement.